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**King et al.**

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(54) **APPARATUS AND METHOD FOR HIGH EFFICIENCY OPERATION OF FUEL CELL SYSTEMS**

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USPC ..... 429/400, 428, 432  
See application file for complete search history.

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 165 days.

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**Related U.S. Application Data**

(63) Continuation of application No. 12/326,171, filed on Dec. 2, 2008, now Pat. No. 8,486,570.

(57) **ABSTRACT**

(51) **Int. Cl.**

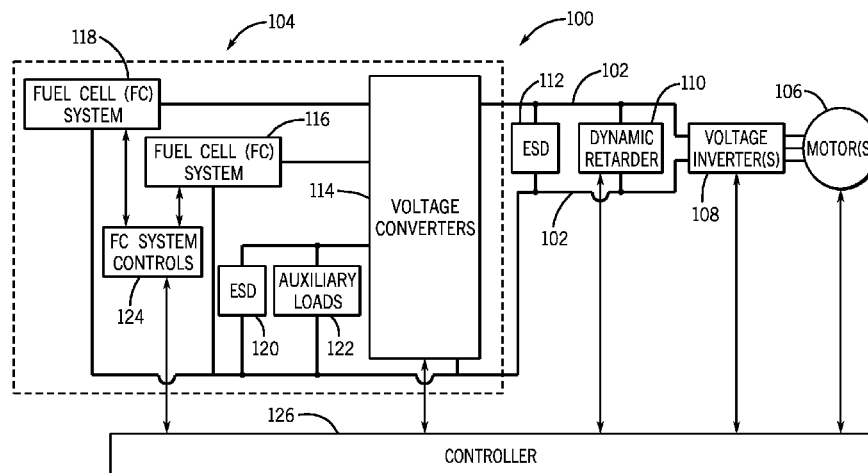
**H02P 27/06** (2006.01)  
**H01M 8/04** (2006.01)  
**H01M 16/00** (2006.01)  
**H02J 7/34** (2006.01)  
**H02J 1/00** (2006.01)

A drive circuit comprising a DC bus configured to supply power to a load, a first fuel cell coupled to the DC bus and configured to provide a first power output to the DC bus, and a second fuel cell coupled to the DC bus and configured to provide a second power output to the DC bus supplemental to the first fuel cell. The drive circuit further includes an energy storage device coupled to the DC bus and configured to receive energy from the DC bus when a combined output of the first and second fuel cells is greater than a power demand from a load, and provide energy to the DC bus when the combined output of the first and second fuel cells is less than the power demand from the load.

(52) **U.S. Cl.**

CPC ..... **H02P 27/06** (2013.01); **H01M 8/0494** (2013.01); **H01M 8/04619** (2013.01); **H01M 8/04947** (2013.01); **H01M 16/006** (2013.01); **H02J 7/34** (2013.01); **H02J 2001/004**

**21 Claims, 8 Drawing Sheets**



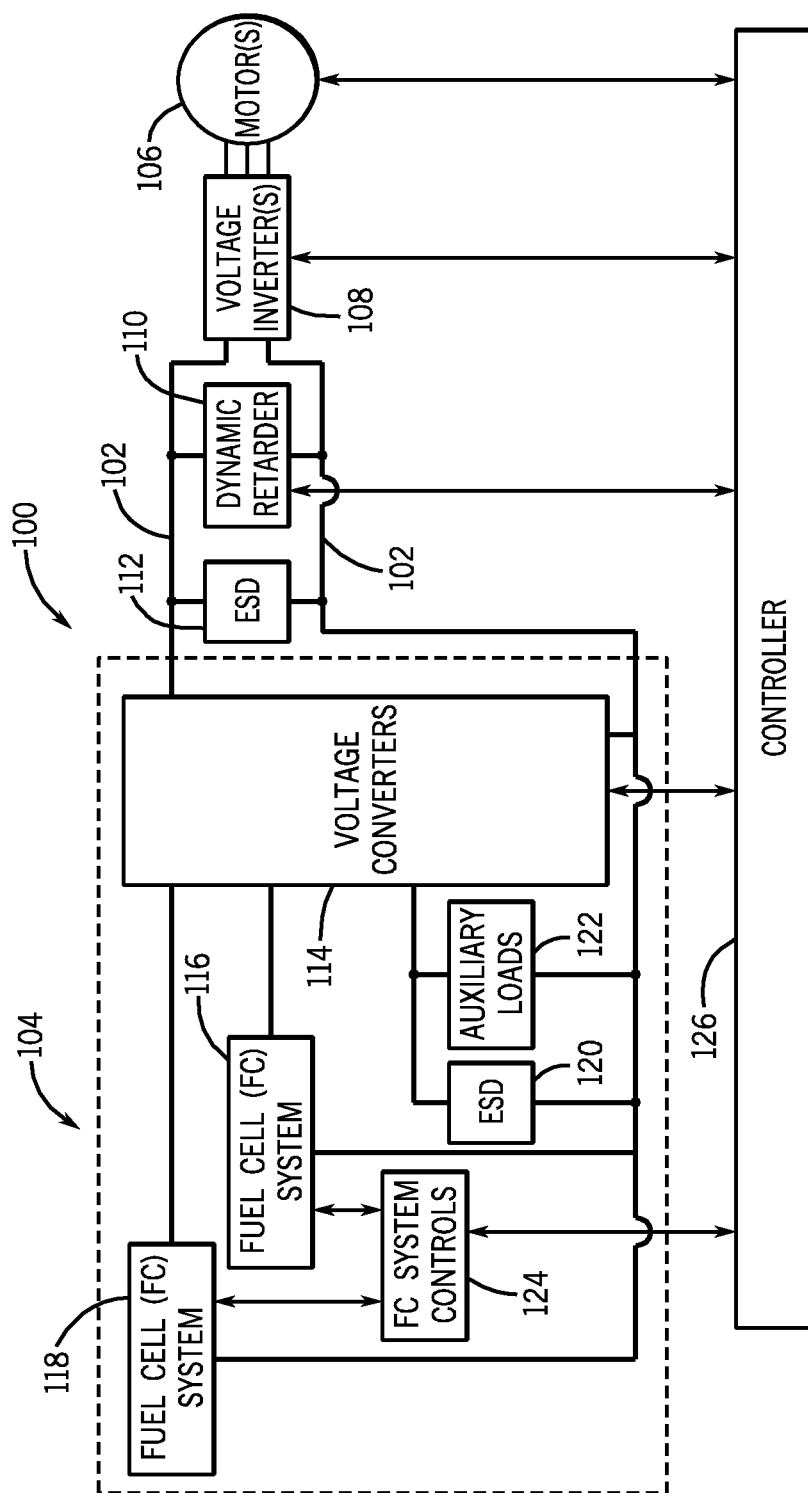


FIG. 1

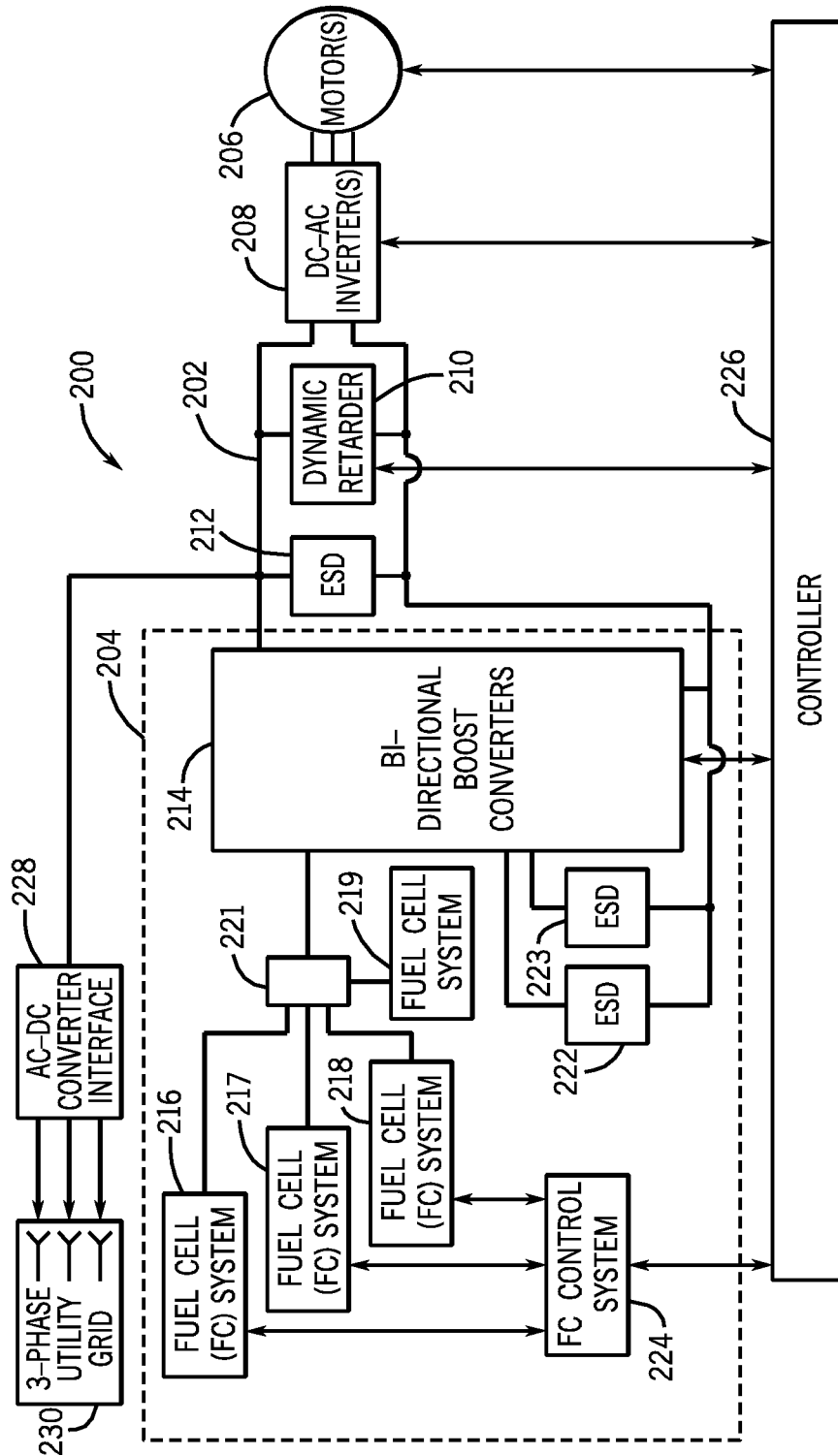


FIG. 2

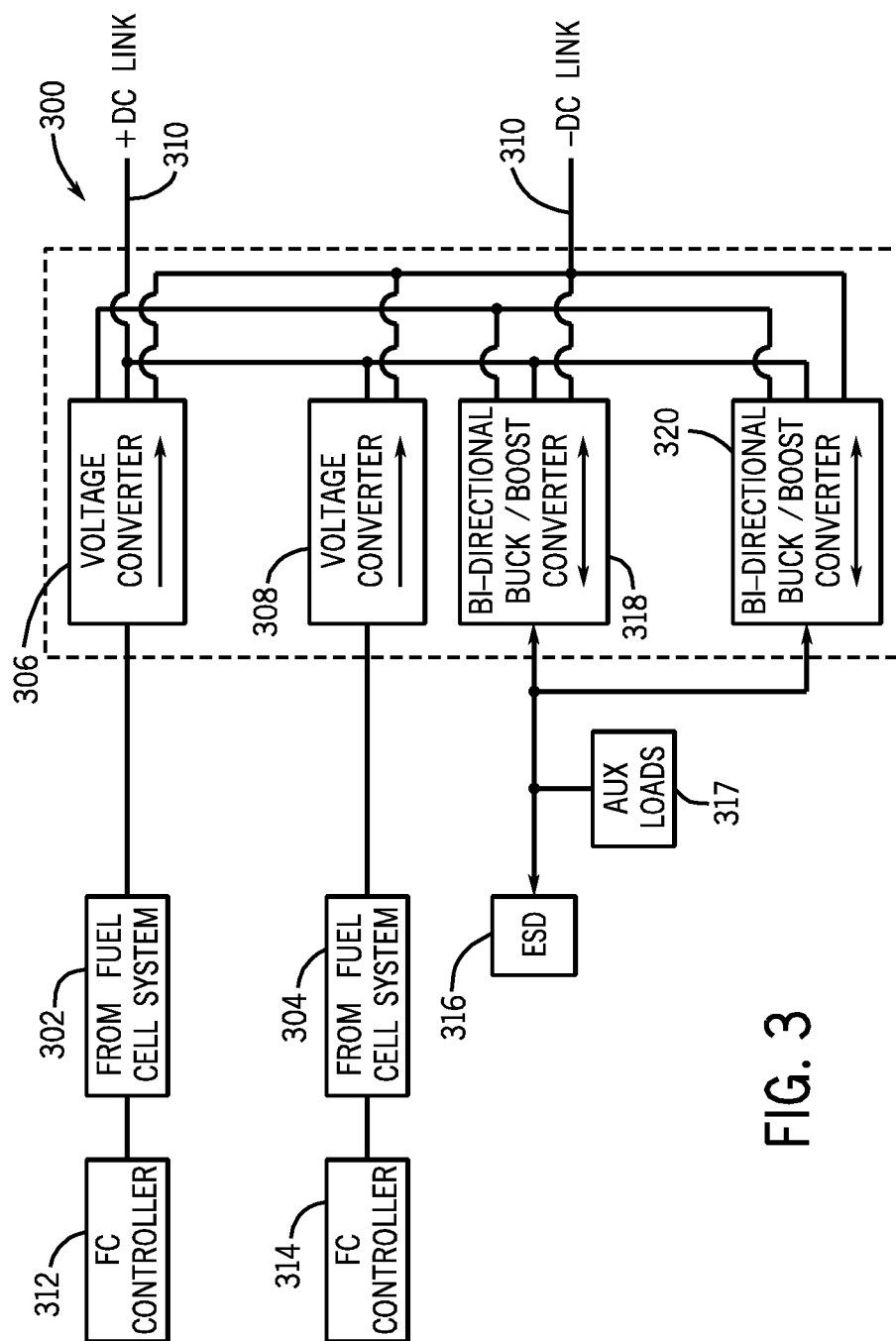


FIG. 3

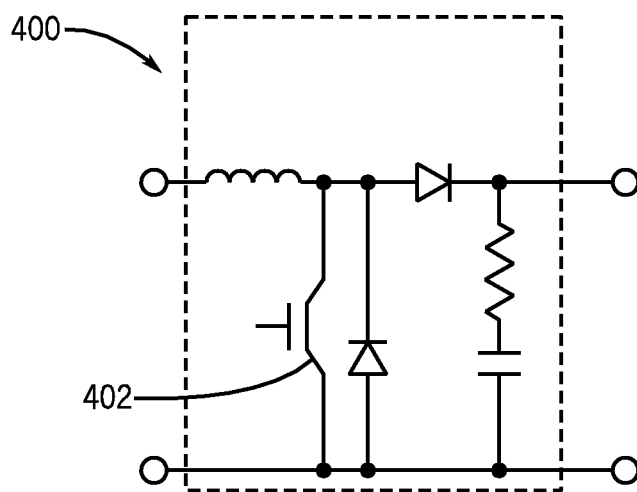


FIG. 4

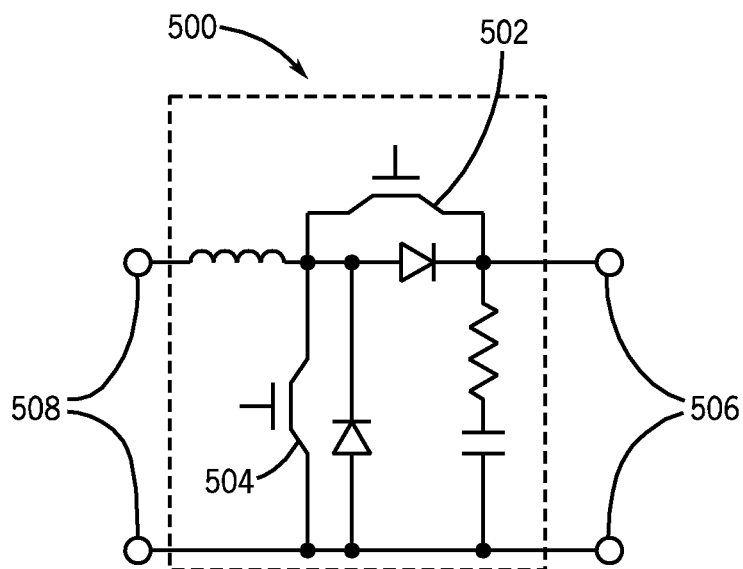


FIG. 5

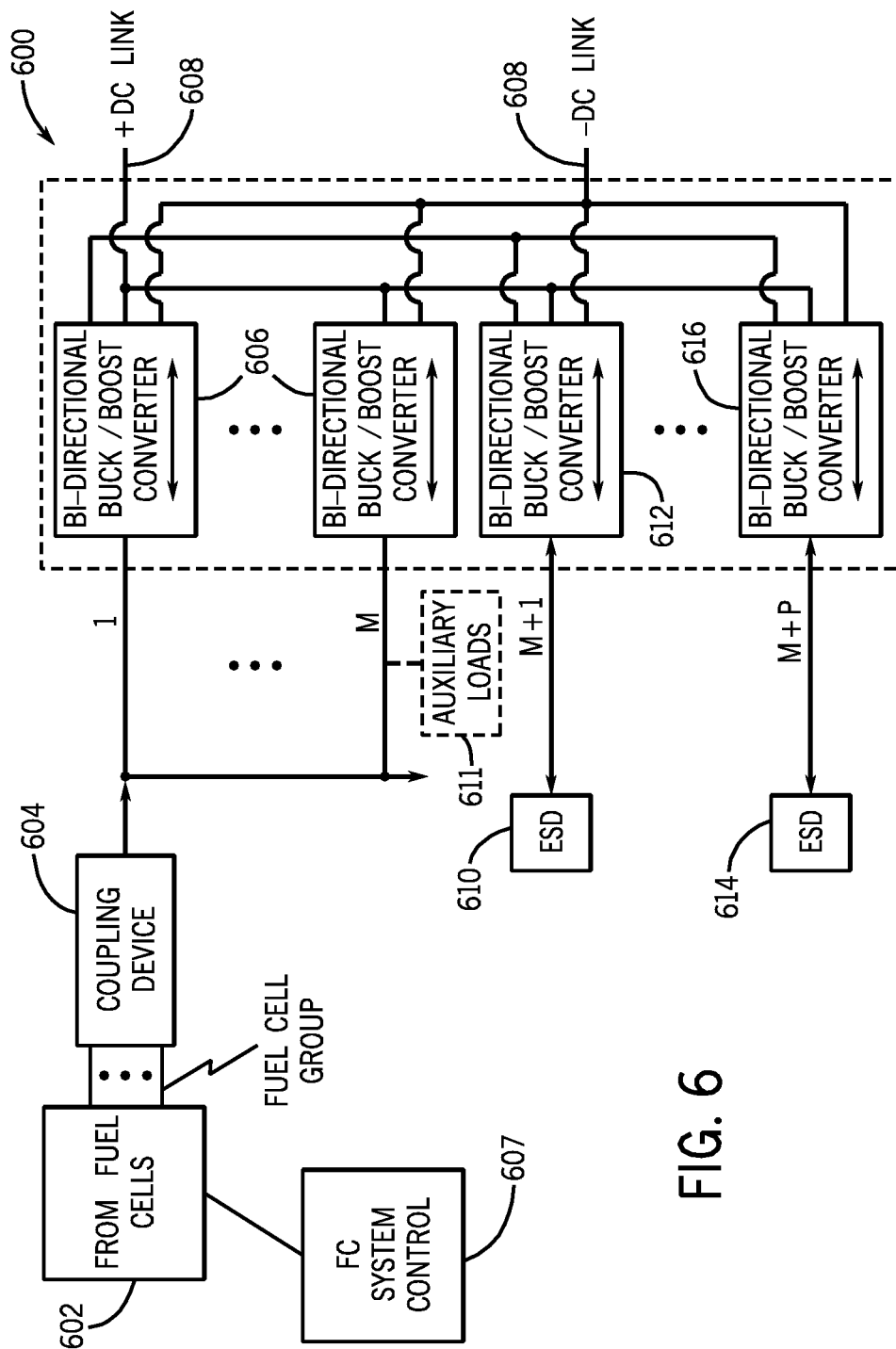


FIG. 6

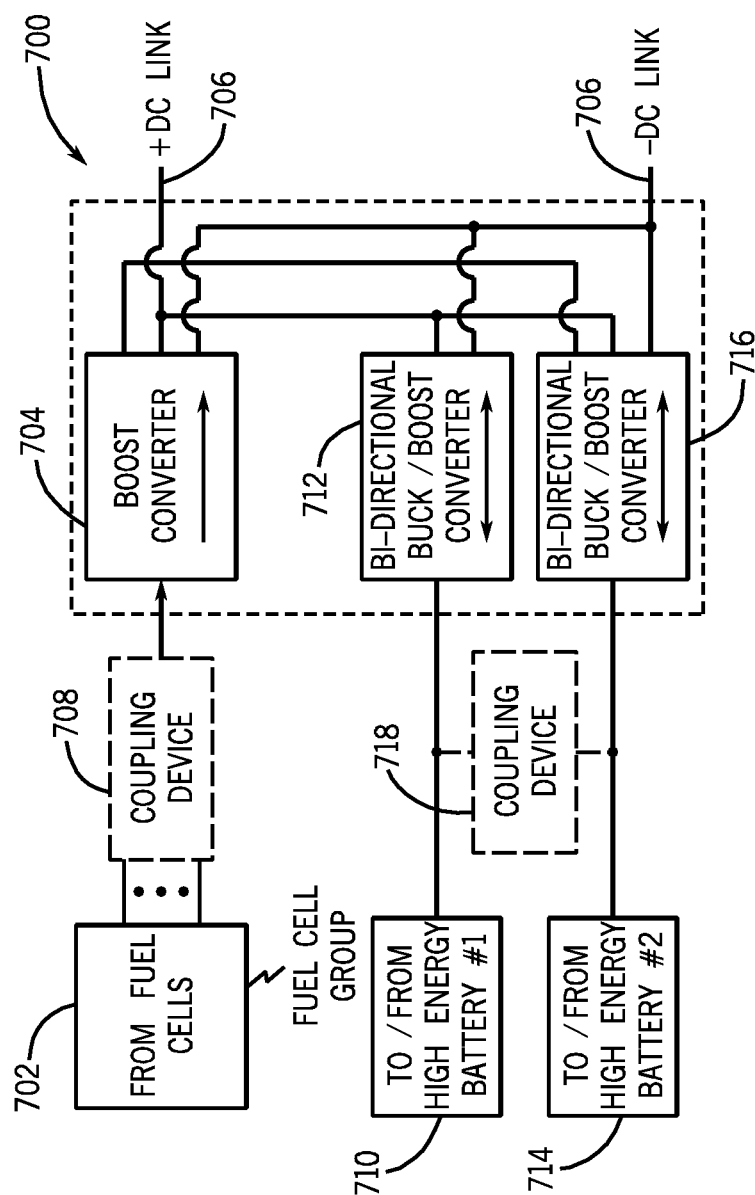


FIG. 7

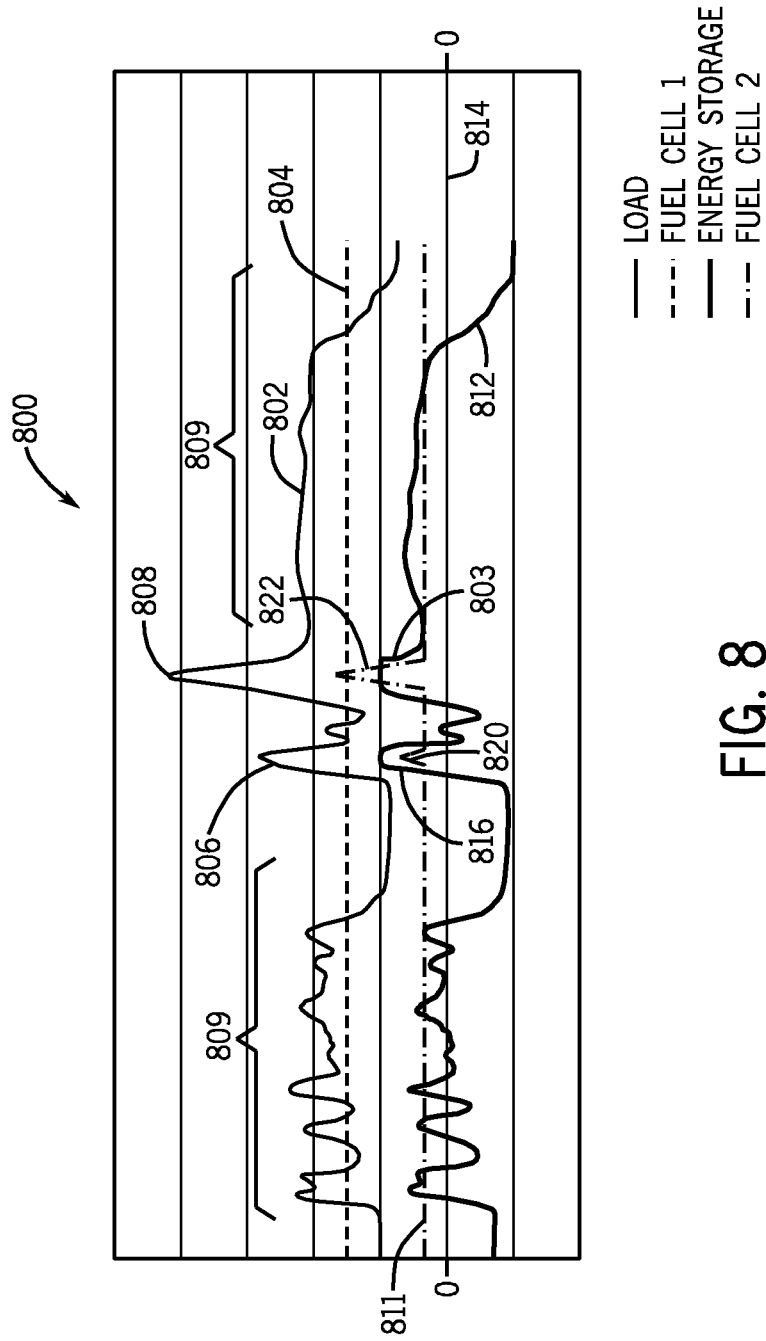


FIG. 8



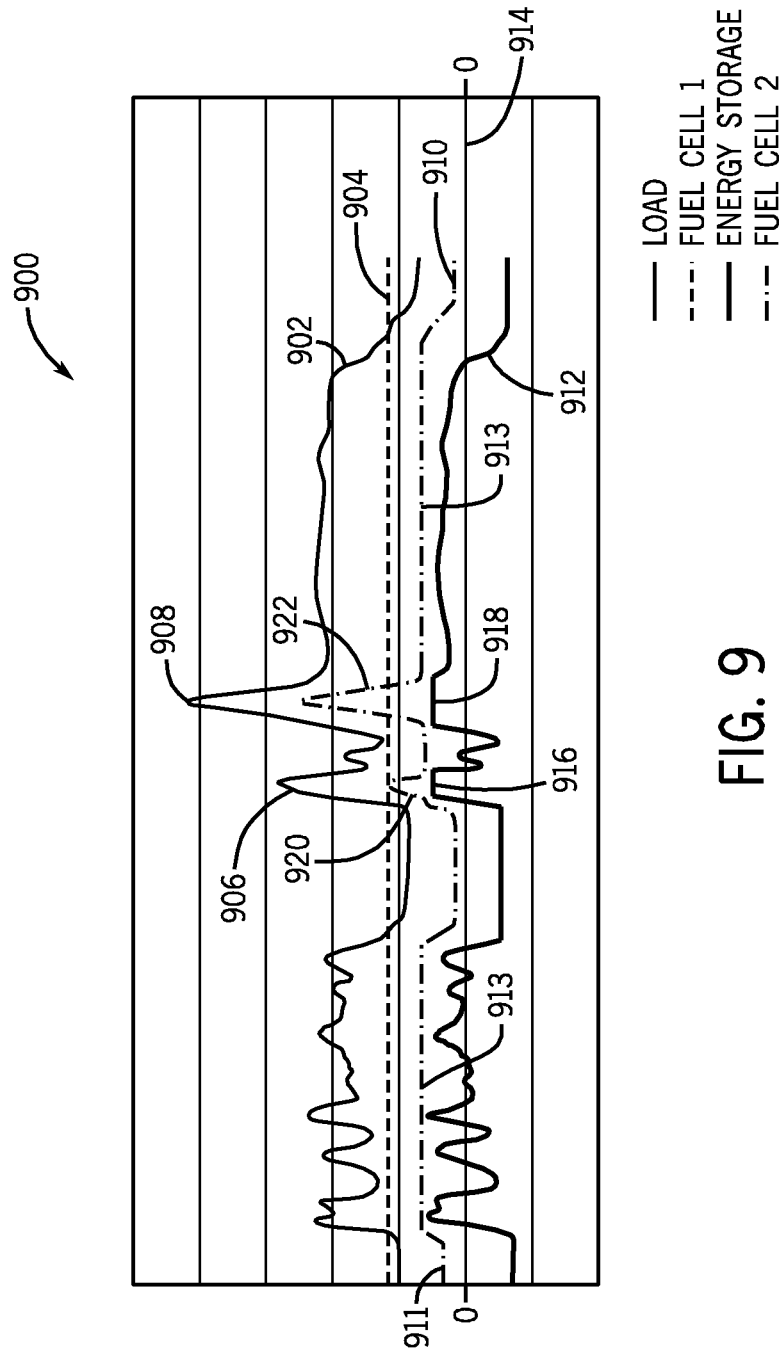


FIG. 9

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# APPARATUS AND METHOD FOR HIGH EFFICIENCY OPERATION OF FUEL CELL SYSTEMS

## CROSS-REFERENCE TO RELATED APPLICATION

The present application is a non-provisional of, and claims priority to, U.S. patent application Ser. No. 12/326,171, filed Dec. 2, 2008, the disclosure of which is incorporated herein by reference.

## BACKGROUND OF THE INVENTION

Embodiments of the invention relate generally to systems that derive their power from fuel cells, and, more specifically, to an apparatus and method for improving the service life and efficiency of such systems.

Fuel cell technology has been incorporated in vehicles ranging from automobiles and buses to forklift trucks. While vehicles using fuel cell propulsion systems may produce low to near-zero emissions, incorporating fuel cell systems into such vehicles typically increases a cost of the vehicle (both in initial cost as well as in operating costs due to a relatively short service life of the fuel cell system) and reduces the range the vehicles may travel. Accordingly, acceptance of fuel cell technology vehicles has generally been limited in the marketplace.

Typically, fuel cell propulsion systems are sized to meet the peak transient requirements for system operation. In a fuel cell vehicle, peak transients generally occur over periods of steep acceleration, during which the system draws significantly more power from the fuel cell than during periods where the vehicle moves at constant speed. Sizing fuel cells to meet peak power requirements during periods of steep acceleration may result in vehicles which have fuel cells that are significantly larger than desired for the majority of driving situations.

Developing fuel cell vehicles with single fuel cells designed to meet the maximum power demand requirements, typically results in fuel cells that are expensive, heavy, and that have a short service life. Because the service lifetime of a fuel cell generally decreases as the total number of transients experienced by the fuel cell increases, having a single large cell may result in frequent replacement of one of the most expensive components in the vehicle. Because the cost of replacing a fuel cell can be a large percentage of the vehicle's total operating costs, decreasing the size of fuel cells and increasing the service life of the fuel cell are two factors in reducing the overall cost of operation of fuel cell vehicles.

It would therefore be desirable to have a fuel cell propulsion system that reduces the number of transients experienced by the fuel cell. It would also be desirable to have a propulsion system in which the size and cost of the fuel cell can be reduced from levels typical for current propulsion systems while offering performance comparable to systems having larger fuel cells.

## BRIEF DESCRIPTION OF THE INVENTION

According to an aspect of the invention, a drive circuit comprising a DC bus configured to supply power to a load, a first fuel cell coupled to the DC bus and configured to provide a first power output to the DC bus, and a second fuel cell coupled to the DC bus and configured to provide a second power output to the DC bus supplemental to the first fuel cell.

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The drive circuit further includes an energy storage device coupled to the DC bus and configured to receive energy from the DC bus when a combined output of the first and second fuel cells is greater than a power demand from the load, and provide energy to the DC bus when the combined output of the first and second fuel cells is less than the power demand from the load.

In accordance with another aspect of the invention, a method of manufacturing that includes configuring a DC link to provide electrical power to a traction motor, the traction motor having a loading on the DC link, coupling a first fuel cell and a second fuel cell to the DC link, each fuel cell configured to output electrical power to the DC link, and coupling a first energy storage device to the DC link, the first energy storage device configured to receive energy from the DC link when a combined power output of the first and second fuel cells is greater than a power demand from a loading and configured to provide energy to the DC link when the combined output of the first and second fuel cells is less than the power demand from the loading.

In accordance with another aspect of the invention, a fuel cell propulsion system including a first fuel cell configured to output power to a vehicle traction motor load, a second fuel cell configured to output power to the vehicle traction motor load, and an energy storage device configured to output power to the vehicle traction motor load. The system further includes a controller configured to regulate energy to and from the energy storage device such that the fuel cells provide energy to the energy storage device when combined power output from the fuel cells exceeds a power demand of the vehicle traction motor, and the energy storage device provides power to vehicle traction motor when combined power output from the fuel cells is less than the power demand of the vehicle traction motor.

Various other features and advantages will be made apparent from the following detailed description and the drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate one preferred embodiment presently contemplated for carrying out the invention.

In the drawings:

FIG. 1 is a block diagram illustrating a fuel cell propulsion system according to an embodiment of the invention.

FIG. 2 is a block diagram illustrating a fuel cell propulsion system according to an embodiment of the invention.

FIG. 3 is a block diagram illustrating a drive circuit usable in the system of FIG. 1.

FIG. 4 is a schematic diagram illustrating an embodiment of a boost converter.

FIG. 5 is a schematic diagram illustrating an embodiment of a bi-directional buck/boost converter.

FIG. 6 is a block diagram illustrating a drive circuit usable in the system of FIG. 2 with alternate boost converter configuration.

FIG. 7 is a block diagram illustrating a drive circuit usable in the system of FIG. 2.

FIG. 8 is a graphical illustration of power output of energy storage elements in a fuel cell propulsion system according to an embodiment of the invention.

FIG. 9 is a graphical illustration of power output of energy storage elements in a fuel cell propulsion system according to an embodiment of the invention.

## DETAILED DESCRIPTION

The invention includes embodiments that relate to hybrid and electric vehicles. The invention also includes embodi-

ments that relate to an auxiliary drive apparatus and to methods for manufacturing auxiliary drive systems.

According to an embodiment of the invention, a hybrid vehicle propulsion system **100** is illustrated in FIG. 1. Electrical power is provided to a DC bus or DC link **102** via a traction motor drive circuit **104**. In this embodiment, a traction motor **106** is coupled to a voltage inverter **108**, which is coupled to a dynamic retarder **110** via DC bus **102**. A high-side energy storage device **112** is coupled to the retarder **110** via DC bus **102** as well. Traction motor drive circuit **104** includes one or more DC-to-DC voltage converters **114** that are coupled to fuel cells **116**, **118**, a low-side energy storage device **120**, and auxiliary loads **122**.

In embodiments of the invention, low side energy storage device **120** may be a battery, an ultracapacitor, a flywheel, or the like. In embodiments of the invention, voltage converters **114** may be a buck regulator, a buck converter, a boost regulator, a boost converter, or a bi-directional buck/boost converter. Fuel cells **116**, **118** are coupled to fuel cell system controls **124**. A controller **126** is coupled to fuel cell system controls **124**, voltage converters **114**, voltage inverter **108**, dynamic retarder **110**, and motor **106**.

In operation, voltage inverter **108** receives a DC power signal provided by traction motor drive circuit **104** to DC bus **102** and converts the DC signal into an AC power signal suitable to drive traction motor **106**, which may be configured to propel a hybrid vehicle (not shown). Traction motor drive circuit **104** generates a DC power signal via fuel cells **116**, **118** and low-side energy storage device **120**. The DC power signal is output to DC bus **102** via the one or more voltage converters **114**. Dynamic retarder **110** is used during the recapture of electrical energy from traction motor **106** during braking. High-side energy storage device **112** is configured to supply electrical power to inverter **108** in one operating mode, during vehicle acceleration for example. In another operating mode, during regenerative braking for example, high-side energy storage device **112** may supply electrical power via the voltage converters **114** to low-side energy storage device **120**, or to auxiliary loads **122**.

Controller **126** regulates the output of both voltage inverter **108** and DC-to-DC voltage converters **114**. Through its control of the output voltage of each of the voltage converters **114**, controller **126** determines what proportion of the electrical energy driving traction motor **106** comes from each of the fuel cells **116**, **118** and from low-side energy storage device **120**. Controller **126** also regulates the operation of fuel cell control system **124**, which is configured to implement on/off sequencing of fuels cells **116**, **118** to extend the service life thereof while providing optimal efficiency independent of the instantaneous power demands of traction motor **106**. While fuel cell control system **124** is depicted as a single element in FIG. 1, in an embodiment of the invention, each fuel cell **116**, **118** has its own fuel cell controller, as discussed below and shown in FIG. 3. Furthermore, although only two fuel cells **116**, **118** are illustrated, embodiments of the invention illustrated herein are not limited to two, but may include more than two fuel cells coupled to voltage converters **114** and controlled by fuel cell system control **124**.

FIG. 2 illustrates a hybrid vehicle propulsion system **200** according to an embodiment of the invention. System **200**, in this embodiment, is a "plug-in" version configured to receive power from a utility grid **230**. And, although illustrated with respect to FIG. 2, it is to be understood that the hybrid systems disclosed herein may all be configured to receive power from a utility grid, such as illustrated with respect to FIG. 2.

According to this embodiment of the invention, hybrid vehicle propulsion system **200** includes a traction motor drive

circuit **204**, which provides electrical power to a DC bus or DC link **202**. In this embodiment, a fraction motor **206** is coupled to a voltage inverter **208**. A dynamic retarder **210** is also coupled to inverter **208** via DC bus **202**. A high-side energy storage device **212**, which may be one of a battery and an ultracapacitor, is coupled to dynamic retarder **210** via DC bus **202** as well. Traction motor drive circuit **204** comprises one or more bi-directional boost converters **214** that are coupled to fuel cells **216**, **217**, **218**, **219**, and to low-side energy storage devices **222**, **223**. The fuel cells **216**, **217**, **218**, **219** are coupled to the boost converters **214** via a plurality of coupling devices **221**, each of which may be a diode, a contactor, a semiconductor switch, or the like.

In embodiments of the invention, low-side energy storage device **222** may be one of a battery, an ultracapacitor, and a flywheel. Fuel cells **216**, **217**, **218**, and **219** are coupled to fuel cell system controls **224**. A controller **226** is coupled to fuel cell system controls **224**, boost converters **214**, and inverter **208**. An AC-to-DC converter **228** is coupled between high-side energy storage device **212** and three-phase utility grid **230**.

In operation, an AC signal from grid **230** is converted by an AC-to-DC converter **228** into a DC signal, the energy from which can be stored in high-side energy storage device **212**, low-side energy storage device **222**, low-side energy storage device **223**, or a combination thereof. In one embodiment, each of the plurality of fuel cells **216-219** is coupled to a distinct bi-directional buck/boost converter of bi-directional buck/boost converters **214**, forming pairs thereof. In this embodiment, the plurality of fuel cells **216-219** may be regenerative or non-regenerative. In an embodiment where fuel cells **216-219** are regenerative fuel cells, bi-directional buck/boost converters **214** permit recharging of fuel cells **216-219** during regenerative braking. The plurality of coupling devices **221** in system **200** may include one coupling device for each fuel cell/bi-directional buck/boost converter pair. When the plurality of coupling devices **221** is a contactor or semiconductor switch, controller **226** can fully isolate a respective fuel cell **216-219** from the remainder of circuit **200**. Electrical energy is thus supplied to traction motor **206** via bi-directional buck/boost converters **214**, which are also configured to deliver electrical energy from traction motor **206** during regenerative braking to the low-side energy storage devices **222**, **223**.

In an embodiment of the invention, system **200** is employed in a multiple fuel cell vehicle. In such an embodiment, controller **226** is configured to operate fuel cells, such as fuel cells **216**, **217**, at a relatively non-varying power output in response to power demands from traction motor **206**. This relatively stable output is maintained independent of the transient or varying power demands from traction motor **206** which may be due to different modes of vehicle operation. However, when there are no power demands on the fuel cells **216**, **217**, such as, for example, at a stop light, controller **226** may instruct fuel cells **216-219** to supply no power until the user accelerates the vehicle. In such a case, the power output from the fuel cells could be reduced. In order for fuel cells **216**, **217** to maintain a non-varying output independent of the varying power demands from traction motor **206**, the output level of fuel cells **216**, **217** should be at or below the minimum power level used during vehicle operation.

During periods of acceleration or when climbing a steep hill, traction motor **206** may demand power in excess of that being supplied by fuel cells **216**, **217**. Such sharp increases or variances in power demand may be referred to as transients and can reduce service life of the fuel cell. Because fuel cells **216**, **217** maintain relatively non-varying power outputs,

power demands in excess of that supplied by fuel cells **216**, **217**, including transient or varying power demands, are met by additional fuel cells, for example **218**, **219**, along with low-side energy storage devices **222**, **223** and high-side energy storage device **212**. In this manner, fuel cell service lifetimes are extended because fuel cells **216**, **217** are not exposed to transient demands. And while fuel cells **218**, **219** supply the supplemental power needed during transient demands, these cells may not have to supply energy when the vehicle operates in a low-demand mode, such as cruising at constant speed or driving at low-speed.

Operating the fuel cells in this manner may also be more economical in that the fuel cells can be smaller than would be possible in a vehicle powered only by a single fuel cell. For example, a single fuel cell vehicle may, at times of peak demand, use 150 kW of power. In this case, the single fuel cell would have to be capable of supplying the 150 kW. As such, the fuel cell could be large and costly to operate and replace and would be exposed to transient power demands, thus limiting the service lifetime of the fuel cell. However, a fuel cell propulsion system according to an embodiment of the invention may include a fuel cell of 40 kW providing a relatively stable or non-varying power output adequate for low-power-demand operating modes. Controller **226** is configured to meet transient power demands using one or more energy storage devices, such as storage devices **212**, **222**, **223**, and using one or more fuel cells, such as fuel cells **218**, **219** to supply supplemental power. Controller **226** could alternate between the two supplemental fuel cells **218**, **219** in responding to transient power demands, thus extending the service life of each cell. Cost savings may be realized through both a longer service life for fuel cells and through the use of smaller, less costly fuel cells.

FIGS. 3, 6, and 7 illustrate traction motor drive circuits **300**, **600**, **700**, respectively, according to embodiments of the invention. Thus, circuits **300**, **600**, **700** may be applicable to the hybrid vehicle propulsion system **100** illustrated in FIG. 1 or to the "plug-in" version of a hybrid vehicle propulsion system **200** illustrated in FIG. 2.

An embodiment of a traction motor drive circuit **300** is illustrated in FIG. 3 and includes two fuel cells **302**, **304**, each of which is coupled to a respective DC-to-DC voltage converter **306**, **308**. Each of DC-to-DC voltage converters **306**, **308** may be one of a uni-directional boost converter and a bi-directional buck/boost converter. Uni-directional boost converters would not supply recharging voltage to fuel cells **302**, **304** when, for example, fuel cells **302**, **304** are non-regenerative-type cells. In this case, using uni-directional boost converters may provide a cost advantage over bi-directional voltage converters.

DC-to-DC voltage converters **306**, **308** are coupled to DC bus/DC link **310**. Each fuel cell **302**, **304** is coupled to a respective fuel cell controller **312**, **314**. An energy storage device **316**, which may be one of a battery, an ultracapacitor, and a flywheel, is coupled to two bi-directional buck/boost converters **318**, **320**, both of which are coupled to DC bus **310**. Auxiliary loads **317** may also be electrically connected to energy storage device **316**, and receive power from energy storage device **316** or from DC link through one or more bi-directional buck/boost converters **318**, **320**. Though only two fuel cells **302**, **304**, two fuel cell controllers **312**, **314**, and two DC-to-DC voltage converters **306**, **308** are illustrated, one skilled in the art will recognize that embodiments of system **300** may include more than two fuel cells, fuel controllers and voltage converters. Accordingly, one skilled in the art will recognize that embodiments of system **300** may include more than two bi-directional buck/boost converters

**318**, **320**, with each of the more than two bi-directional buck/boost converters coupled to DC bus **112** and energy storage device **316**.

Power output of fuel cells **302**, **304** is controlled by fuel cell controllers **312**, **314**, respectively. Together, the individual fuel cell controllers constitute a fuel cell control system, such as fuel cell control system **224** shown in FIG. 2. In operation, each of the DC-to-DC voltage converters **306**, **308** boosts the voltages from fuel cells **302**, **304** when commanded by controllers **312**, **314** and supplies the boosted voltage to DC bus/link **310**. Similarly, when commanded to do so by controller **226**, bi-directional buck/boost converters **318**, **320** boosts the voltage from energy storage device **316** and supplies the boosted voltage to DC bus **310**.

The level to which the output voltages of fuel cell **302**, **304** are boosted, or stepped up, depends on the manner in which DC-to-DC voltage converters **306**, **308** are regulated by controller **226**. Similarly, the level to which the output voltage of energy storage device **316** is boosted depends on the manner in which bi-directional buck/boost converters **318**, **320** are regulated by controller **226**.

FIG. 4 illustrates an exemplary boost converter **400** usable in embodiments of boost converters herein. Boost converter **400** has a transistor or switch **402** used to control the output voltage of the device **400**. In an embodiment of the invention, a controller such as controller **226** (shown in FIG. 2) opens and closes switch **402** using pulse-width modulation (PWM) to generate the desired output voltage. Pulse-width modulation of a power supply, such as fuel cell **302** (shown in FIG. 3) and DC-to-DC voltage converter **306** (shown in FIG. 3), involves modulation of the power supply duty cycle. The resulting output is a series of square waves. By controlling the timing of the square waves, the power supply output signal can be made to simulate a range of DC voltage values.

FIG. 5 shows an exemplary bi-directional buck/boost converter **500** usable in embodiments of bi-directional buck/boost converters herein. Bi-directional buck/boost converter **500** has two transistor or switches **502**, **504** used to control the output voltage of the device. In an embodiment of the invention, controller **226** (shown in FIG. 2) operates the transistors **502**, **504** using PWM to generate the desired output voltage. Power can flow in both directions through converter **500**. However, the output voltage can be boosted only in one direction, that is, when power is output at a first terminal **506**. For power flowing in the other direction and output to a second terminal **508**, bi-directional converter **500** acts as a buck, or step-down, converter.

FIG. 6 illustrates an embodiment of a fraction motor drive circuit **600** in which a plurality of fuel cells **602** is coupled to a coupling device **604**. In an alternate embodiment of invention, circuit **600** includes one coupling device for each of the plurality of fuel cells **602**. The combined output of the plurality of fuel cells **602** is coupled through coupling device **604** to a plurality of bi-directional buck/boost converters **606**. In an alternate embodiment of the invention, the combined output of the plurality of fuel cells **602** is also electrically coupled through coupling device **604** to auxiliary loads **611** (shown in phantom). Auxiliary loads **611** can be powered directly from fuel cells **602** or via bi-directional buck/boost converters **606** using power from DC Link **608**. Fuel cells **602** are also coupled to fuel cell control system **607**, which, in an embodiment of the invention, includes a separate fuel cell controller (not shown) for each of the plurality of fuel cells **602**. Each of the plurality of bi-directional buck/boost converters **606** is coupled to DC link or bus **608**. A first energy storage device **610**, which may be a battery or an ultracapacitor, is coupled to a first bi-directional buck/boost converter **612**. A second

energy storage device **614**, which may be a battery, an ultra-capacitor, or a flywheel, is coupled to a second bi-directional buck/boost converter **616**. First and second bi-directional buck/boost converters **612**, **616** are coupled to DC bus **608**. One skilled in the art will recognize that circuit **600** is not limited to two energy storage devices but may include a plurality of energy storage devices coupled to one or more bi-directional buck/boost converters.

The use of bi-directional buck/boost converters **606** allows for recharging of regenerative-type fuel cells **602** during regenerative braking. Similarly, bi-directional buck/boost converters **612**, **616** allow for recharging of energy storage devices **610**, **614** during regenerative braking. Having multiple energy storage devices **610**, **614** may increase the amount of electrical energy available to devices powered from DC bus **608**. However, the amount of electrical energy supplied to DC bus **608** via energy storage devices **610**, **614** is determined by the manner in which the voltage output of each of bi-directional buck/boost converters **612**, **616** is regulated.

Bi-directional buck/boost converters **606** step up the voltage output from the plurality of fuel cells **602** and supply the stepped up voltage to DC bus **608**. Similarly, bi-directional buck/boost converters **612**, **616** step up the voltages from energy storage devices **610**, **614** and supplies the stepped up voltages to DC bus/DC link **608**. The amount of electrical energy output by fuel cells **602** is determined by the manner in which fuel cell output is regulated by fuel cell control system **607**. During low-speed driving or cruising at constant speed, fuel cell control system **607** may be commanded to operate a subset of the plurality of fuel cells **602** to output power at a non-varying rate to propel the vehicle. During periods of acceleration, when more power is needed, circuit **600** may meet the transient power demands by drawing supplemental power from energy storage devices **610**, **614** and from fuel cells **602**.

FIG. 7 illustrates a traction motor drive circuit **700** according to an embodiment of the invention. Traction motor drive circuit **700** includes a plurality of fuel cells **702** whose combined output is coupled to a boost converter **704** coupled to DC link **706**. In an alternate embodiment of circuit **700**, each of the plurality of fuel cells **702** is coupled to a coupling device **708** (shown in phantom), which may be a semiconductor switch, a diode, a contactor, or the like. A first energy storage device **710** is coupled to a first bi-directional buck/boost converter **712**, and a second energy storage device **714** is coupled to a second bi-directional buck/boost converter **716**. Each of the first and second energy storage devices **710**, **714** may be a battery, an ultracapacitor, or a flywheel. Each of the first and second bi-directional buck/boost converters **712**, **716** is coupled to DC link **706**.

In operation, the output voltage of the plurality of fuel cells **702** is stepped up by boost converter **704** and output to DC link **706**. Similarly, the output voltages of storage devices **710**, **714** are boosted by converters **712**, **716**, respectively, and supplied to DC bus **706**. In an alternate embodiment, a contactor- or switch-type coupling device **708** may be operated to isolate the plurality of fuel cells **702** from the remainder of circuit **700**. Alternate embodiments may also include a coupling device **718** (shown in phantom) coupled between the outputs of first energy device **710** and second energy device **714**. Coupling device **718** could be used to recharge one energy storage device by a second energy storage device. For example, if first energy storage device **710** is a battery and second energy storage device **714** is an ultracapacitor, the battery **710** could supply the ultracapacitor **714** with electrical energy via coupling device **718**.

FIG. 8 is a graphic illustration of a power output plot **800** of an exemplary hybrid vehicle propulsion system having two fuel cells, a battery, and a load such as an electric motor according to embodiments of the invention. A power demand curve **802** illustrates an exemplary power demand of the electric motor. A plurality of curves **804** and **811** respectively illustrate power provided by first and second fuel cells. An energy storage device power curve **812** illustrates power output by an energy storage device such as, for example, a battery.

The first fuel cell is operated to experience minimum transients, and the second fuel cell is operated to experience transients when limits of the energy storage device have been reached according to embodiments of the invention. As illustrated, first fuel cell power **804** is stable or non-varying despite the transiently varying power demand **802**. Second fuel cell power **811** is stable during periods when the electric motor power demand **802** is less than the combined power outputs of first fuel cell **804**, second fuel cell **811**, and battery power **812** such as during period **809**. During period **809**, the power demand **802** is variable, and at times exceeds the total output of the first and second fuel cells **804**, **811**, and at other times is less than the total output of the first and second fuel cells **804**, **811**. When the power demand is less than the combined power output of the first and second fuel cells **804**, **811**, output **812** from the battery is not needed, and the excess fuel cell energy charges the battery. As illustrated in FIG. 8, when battery power **812** drops below a zero axis **814**, the battery may absorb excess power from the first and second fuel cells.

At times during operation, power demand **802** may experience spikes **806**, **808** that exceed the stable output of both fuel cells **802**, **811** and battery **812**. For example, battery power output **812** may be limited by the physical properties of the battery as illustrated by plateaus **803**, **816**. Under such occurrences of spikes **806**, **808**, when battery power **812** reaches maximum battery output **803**, **816**, power output of the second fuel cell transiently increases, respectively, at **820** and **822** to meet the additional power demand.

Thus, because the battery initially responds to transient power demands exceeding the stable power outputs of the two fuel cells, the second fuel cell responds to transient demands that exceed the combined stable power outputs of the two fuel cells and the power output of the battery. Reducing exposure of the second fuel cell to transient power demands when limits of the battery have been reached increases the service life of the second fuel cell. Further, because the first fuel cell does not respond to power demand transients such as at spikes **806**, **808**, the first fuel cell has a longer service life and, further, does not have to be sized to meet power demands greater than the stable output **804**.

FIG. 9 is a graphic illustration **900** of power output of an exemplary hybrid vehicle propulsion system having two fuel cells, a battery and a load, such as an electric motor, according to embodiments of the invention. That illustrated in FIG. 9 is similar to that illustrated in FIG. 8. However, in this embodiment the maximum power output of the battery is halved and the second fuel cell is caused to experience greater transient fluctuations under the same assumed loading conditions.

Referring now to FIG. 9, a power output plot **900** is illustrated according to an embodiment of the invention. Power output plot **900** shows a power demand curve **902** similar to power demand curve **802** shown in FIG. 8. A power output curve **904** of a first fuel cell shows stable or non-varying power output despite varying power demands of the electric motor **902**. A power output curve **910** is plotted of a second fuel cell having half the power output of the second fuel cell

used for output curve **811** illustrated in FIG. **8**. An energy storage device or battery power curve from **912** illustrates power output by, for example, a battery having half the power output of the battery used for output curve **802** illustrated in FIG. **8**. Curve **910** shows a non-zero base power output **911** that is stable while the electric motor power demand from curve **902** is less than the stable power output of the first fuel cell **904**. Curve **910** shows another non-zero base power output **913** that is stable while the electric motor power demand from curve **902** is greater than the stable power output of the first fuel cell **904** and while the electric motor power demand from curve **902** is less than a maximum battery power output as illustrated by plateaus **916**, **918** of curve **912**.

Because the battery, in this embodiment, has half the power output of that used in FIG. **8**, the second fuel cell is operated to respond to more transient demands than under the same load conditions as those illustrated in FIG. **8** such that the first fuel cell experiences minimum transients. When the electric motor power demand **902** is less than the combined power output of the first and second fuel cells **904**, **910**, the excess fuel cell energy charges the battery as illustrated when battery power output line **912** drops below the zero axis **914** on graph **900**, which indicates that the battery is absorbing excess power from the first and second fuel cells. The battery power output **912** adds supplemental power to the first and second fuel cell power outputs **904**, **910** when the power demand **902** exceeds the power output **904** of the first fuel cell and the base power output **913** of the second fuel cell. When the battery output reaches its maximum shown at **916**, **918**, the power output of the second fuel cell increases at **920**, **922** to meet the power demanded at **906**, **908**. Because the battery initially responds to transient demands exceeding the stable power outputs of the two fuel cells, the responses of the second fuel cell to transient power demands are reduced. However, because the battery power output maximum is less than that illustrated in FIG. **8**, the transient response requirements of the second fuel cell are increased.

Thus, between the two illustrations of FIGS. **8** and **9**, one skilled in the art will recognize that a tradeoff may be made between battery capacity and transient requirements of the second fuel cell. A large battery capacity may reduce or eliminate the transient requirements of the fuel cell under designated operating conditions. However, it does so at the expense of a larger and more expensive battery. Conversely, a smaller battery capacity may result in increased transient requirements of the second fuel cell, thus negatively impacting its life. As such, the up-front cost of a large battery may be used to offset the long-term life costs of a fuel cell, and vice versa, according to embodiments of the invention.

According to one embodiment of the invention, a drive circuit comprising a DC bus configured to supply power to a load, a first fuel cell coupled to the DC bus and configured to provide a first power output to the DC bus, and a second fuel cell coupled to the DC bus and configured to provide a second power output to the DC bus supplemental to the first fuel cell. The drive circuit further includes an energy storage device coupled to the DC bus and configured to receive energy from the DC bus when a combined output of the first and second fuel cells is greater than a power demand from the load, and provide energy to the DC bus when the combined output of the first and second fuel cells is less than the power demand from the load.

In accordance with another embodiment of the invention, a method of manufacturing that includes configuring a DC link to provide electrical power to a traction motor, the traction motor having a loading on the DC link, coupling a first fuel cell and a second fuel cell to the DC link, each fuel cell

configured to output electrical power to the DC link, and coupling a first energy storage device to the DC link, the first energy storage device configured to receive energy from the DC link when a combined power output of the first and second fuel cells is greater than a power demand from a loading and configured to provide energy to the DC link when the combined output of the first and second fuel cells is less than the power demand from the loading.

In accordance with yet another embodiment of the invention, a fuel cell propulsion system including a first fuel cell configured to output power to a vehicle traction motor load, a second fuel cell configured to output power to the vehicle traction motor load, and an energy storage device configured to output power to the vehicle traction motor load. The system further includes a controller configured to regulate energy to and from the energy storage device such that the fuel cells provide energy to the energy storage device when combined power output from the fuel cells exceeds a power demand of the vehicle traction motor, and the energy storage device provides power to vehicle traction motor when combined power output from the fuel cells is less than the power demand of the vehicle traction motor.

While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. A drive circuit comprising:

a DC bus;  
a voltage converter assembly coupled to the DC bus;  
a first fuel cell coupled to the voltage converter assembly;  
a second fuel cell coupled to the voltage converter assembly; and

a controller programmed to:

operate the first fuel cell to deliver a first power output to the voltage converter assembly during a first mode of operation and deliver a second power output to the voltage converter assembly during a second mode of operation, the second power output different from the first power output; and

operate the second fuel cell to deliver a third power output to the voltage converter assembly during the first and second modes of operation.

2. The drive circuit of claim 1 wherein the first and second power outputs are greater than zero.

3. The drive circuit of claim 1 wherein the controller is further programmed to:

control the first fuel cell to supply the first output power at a non-varying rate; and

simultaneously control the second fuel cell to supply the third output power at a varying rate.

4. The drive circuit of claim 3 wherein the controller is further programmed to implement an on/off sequencing of the second fuel cell to cause the second fuel cell to supply the third output power at the varying rate.

5. The drive circuit of claim 1 further comprising an energy storage device coupled to the DC bus via the voltage converter assembly; and

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wherein the controller is further programmed to control the energy storage device to deliver a supplemental output power to the voltage converter assembly.

6. The drive circuit of claim 5 wherein the energy storage device comprises one of a battery, an ultracapacitor, and a flywheel.

7. The drive circuit of claim 1 wherein the first and second fuel cells comprise regenerative fuel cells.

8. The drive circuit of claim 1 wherein the first fuel cell has a first power rating; and wherein the second fuel cell has a second power rating, lower than the first power rating.

9. The drive circuit of claim 1 wherein the voltage converter assembly comprises a plurality of bi-directional buck/boost converters.

10. A method of operating a fuel cell propulsion system comprising:

operating a controller programmed to cause a first fuel cell to deliver a first output to a DC-to-DC converter assembly during a first mode of operation;

operating a controller programmed to cause the second fuel cell to deliver a second output to the DC-to-DC converter assembly during the first mode of operation;

operating a controller programmed to cause the first fuel cell to deliver the second output to the DC-to-DC converter assembly during a second mode of operation;

operating a controller programmed to cause the second fuel cell to deliver the first output to the DC-to-DC converter assembly during the second mode of operation; and

operating a controller programmed to cause the DC-to-DC converter assembly to boost the first and second outputs and supply the boosted outputs to a DC link.

11. The method of claim 10 further comprising:

operating a controller programmed to cause the first fuel cell to deliver a non-varying output to the DC-to-DC converter assembly during the first mode of operation; and

operating a controller programmed to cause the second fuel cell to deliver a varying output to the DC-to-DC converter assembly during the first mode of operation.

12. The method of claim 11 further comprising operating a controller to sequence the second fuel cell between an on condition and an off condition during the first mode of operation.

13. The method of claim 10 further comprising operating a controller programmed to cause the DC-to-DC converter assembly to permit recharging of the first and second fuel cells during a third mode of operation.

14. The method of claim 10 further comprising operating a controller programmed to cause an energy storage device to deliver a third output to the DC-to-DC converter assembly during the first mode of operation.

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15. The method of claim 10 further comprising:

operating a controller programmed to cause the first fuel cell to deliver a first output to the DC-to-DC converter assembly during a first mode of operation; and

operating a controller programmed to cause the second fuel cell to deliver a second output to the DC-to-DC converter assembly during the first mode of operation, the second output different than the first output.

16. A fuel cell propulsion system comprising:

a vehicle traction motor;

a DC bus coupled to the vehicle traction motor via an inverter;

a DC-to-DC converter assembly coupled to the DC bus;

a first fuel cell coupled to the DC bus via the DC-to-DC converter assembly;

a second fuel cell coupled to the DC bus via the DC-to-DC converter assembly; and

a controller programmed to:

operate the first fuel cell to deliver a first power output to the DC-to-DC converter assembly during a high-power-demand operating mode; and

operate the second fuel cell to deliver a second power output to the DC-to-DC converter assembly during a low-power-demand operating mode.

17. The fuel cell propulsion system of claim 16 wherein the controller is further programmed to:

during a first mode of operation, simultaneously operate the first fuel cell to deliver the first power output and operate the second fuel cell to deliver the second power output; and

during a second mode of operation, simultaneously operate the first fuel cell to deliver the second power output and operate the second fuel cell to deliver the first power output.

18. The fuel cell propulsion system of claim 17 wherein the first and second power outputs are greater than zero.

19. The fuel cell propulsion system of claim 16 further comprising an energy storage unit coupled to the DC-to-DC converter assembly; and

wherein the controller is further programmed to operate the energy storage unit to supply a power output equal to a difference between a requested operating power of the vehicle traction motor and a combined power output of the first and second fuel cells.

20. The fuel cell propulsion system of claim 16 wherein the controller is further programmed to:

operate the first fuel cell to provide a variable power output; and

operate the second fuel cell to provide a non-variable power output.

21. The fuel cell propulsion system of claim 16 wherein the first and second fuel cells comprise regenerative fuel cells.

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